# FIELD EVALUATION OF BASAL CROP COEFFICIENTS FOR CORN BASED ON GROWING DEGREE DAYS, GROWTH STAGE, OR TIME

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**ABSTRACT.** *Basal crop coefficients for estimating corn evapotranspiration that are based on time do not account for variations in plant development that occur due to differences in growing season temperature, hybrid maturity length, and planting date. Crop coefficients based on growing degree days (GDD) or observed growth stage (GS) are available that would adjust to abnormal growing conditions. This article reports the results of Colorado field tests of corn basal crop coefficients derived in Nebraska based on either GS or GDD. These crop coefficients were tested for a range of planting dates and corn hybrid maturities. Generally, these crop coefficients estimated corn evapotranspiration (ETcorn) more closely to water balance measurements of ET than did time-based (TB) crop coefficients. Coefficients based on observed growth stage or growing degree days simplify ET prediction and irrigation scheduling because adjustments for abnormal environmental conditions or planting dates are not necessary.* ***Keywords.*** *Evapotranspiration, Irrigation, Crop coefficients.*

Corn evapotranspiration (ETcorn) can be predicted from models based on weather parameters (Jensen et al., 1990). These models predict reference evapotranspiration (ET) which is then multiplied by a crop coefficient (Kco) to give estimated ET (Wright, 1982). Currently, Kco values widely used are based on time indexed from dates of planting and full cover. These time-based Kco work well under average planting and growing season conditions, but may require periodic adjustment when nonaverage conditions occur. Crop coefficients based on growing degree days (GDD) or growth stage (GS) can automatically adjust for differences in growth due to nonaverage weather conditions.

Amos et al. (1989) developed a basal crop coefficient curve in Kansas based on the fraction of thermal units needed to mature the corn crop. They concluded that the use of fraction of thermal units as the crop coefficient base scale allowed for a general and accurate use of the base crop coefficient curve across corn cultivars requiring various thermal unit totals from emergence to physiological maturity.

Similarly, Sammis et al. (1985) derived a crop coefficient curve for corn based on growing degree days. They concluded that this crop coefficient curve was applicable in different years and different locations in New Mexico having different climatic conditions because it accounted for differences in plant development rate associated with temperature differences.

Stegman (1988) analyzed both mean and basal crop coefficient curves for corn from Kansas, North Dakota, Nebraska, and Colorado to determine the degree of commonality or transferability between Great Plains sites. He found that when the basal crop coefficient curves from both Nebraska and North Dakota were based on fraction of seasonal growing degree days, essentially the same relationship was defined. He further concluded that measured corn ET was more closely predicted during both above-normal and below-normal temperature growing seasons by GDD-based crop coefficient curves than by time-based curves.

Hinkle et al. (1984) derived basal crop coefficients for corn based on observed GS or on GDD. This work was done in west-central and eastern Nebraska, with ETcorn measured from weighing lysimeters.

The purpose of this study was to evaluate the ET-prediction accuracy of these GS- and GDD-based corn basal crop coefficients derived in Nebraska under varying planting date conditions for hybrids varying in number of days to maturity. The results are compared to both ETcorn predicted with a time-based Kco equation, and to measured ETcorn from water balance calculations.

## PROCEDURE

The field evaluation was conducted at the Central Great Plains Research Station near Akron, Colorado, during the 1991 and 1992 growing seasons. The soil type at this location is a Rago silt loam (fine montmorillonitic mesic Pachic Argiustoll). Three corn hybrids varying in days to maturity were planted at three planting dates (table 1) to give a range of conditions varying from the normal planting date and temperature conditions. Each hybrid/planting date area was 24 × 122 m, divided into four replicate plots with dimensions of 24 × 30 m. Rows were 0.76 m apart, oriented north-south. Final plant

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Trade names and company names are included for the benefit of the reader and do not imply any endorsement or preferential treatment of the product by the authors or the USDA.

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**Table 1. Corn hybrids with respective days to maturity and GDD to maturity, and planting dates**

| Corn Hybrid | Days to Maturity* | GDD to Maturity (° C)† |
|---|---|---|
| Pioneer 3902 | 91 | 1267 |
| Pioneer 3732 | 101 | 1336 |
| Pioneer 3540 | 109 | 1422 |
| Planting Dates | 1991 | 1992 |
| Early | 25 April | 30 April |
| Midseason | 29 May | 19 May |
| Late | 18 June | 10 June |

* Company maturity ratings.

† Measured at Akron, Colo., during 1987-1989 growing seasons using 10-32 heat stress method.

population was 73 910 plants $ha^{-1}$. Growing degree days to maturity were determined from observations of these hybrids at Akron, Colorado, during the 1987 to 1989 growing seasons.

Weather data were measured with an automated weather station located over an area of unirrigated grass, 300 m east of the experimental plot area. Parameters measured were daily maximum and minimum air temperature (°C), daily total solar radiation ($MJ\ m^{-2}\ d^{-1}$), daily average wind speed at 3 m ($m\ s^{-1}$), and hourly average relative humidity (%). Daily average vapor pressure (kPa) was calculated from the hourly temperature and humidity measurements by the weather station datalogger (CR21, Campbell Scientific, Logan, Utah) using the saturation vapor pressure algorithm of Lowe (1976). These data were used to calculate reference ET (ETr) by the Penman-Monteith equation from the REF-ET computer program (Allen, 1990). Precipitation was recorded manually from a standard raingage in the plot area.

Soil water measurements were taken weekly with a neutron probe at depths of 0.45, 0.75, 1.05, 1.35, and 1.65 m. Soil water in the 0.00 to 0.30 m layer was measured by time-domain reflectometry (TDR). Neutron probe access tubes and TDR waveguides were located in the interrow space between corn rows in the center of each of the four replicate plots in each of the hybrid/planting date combinations. Measured corn ET was calculated by the water balance method (Rosenberg et al., 1983) from changes in soil water content plus measured rain and irrigation. We assumed runoff and deep percolation were negligible. The plots were located on level ground, but were furrow-diked on every row to minimize runoff potential. Measurements of soil water content at 1.65 m indicated no movement of water into lower soil depths. The four calculated corn ET values for each hybrid/planting date combination were averaged together to give one value to compare to ET estimated by each of the Kco prediction methods.

Irrigations were applied once a week through solid set, overhead sprinklers. Sprinkler heads were 2.5 m above the soil surface, with 12.2 m between heads, providing uniform water distribution across the plot area. Enough water was applied at each irrigation to bring the 0- to 90-cm soil layer back to field capacity to ensure a nonwater-stressed plant condition. Irrigation application amounts were measured with gages at each soil water measurement location.

Corn growth stage was recorded weekly using the Hanway (1971) scale (0 = emergence, 10 = black layer). Leaf area index (LAI) was measured nondestructively using a Plant Canopy Analyzer (LAI-2000, LI-COR, Inc., Lincoln, Nebr.) at approximately weekly intervals.

Growing degree days were calculated as described by Hinkle et al. (1984) using the 10-32 heat stress method. For this method, the daily maximum temperature was reduced by the amount that the maximum temperature exceeds the upper limit of 32°C (e.g., if the daily maximum temperature were 35°C), then the maximum temperature for the GDD calculation would be (32-3) = 29°C. The base temperature for the GDD calculation was 10°C. Growing degree days were then calculated as:

$$\frac{\text{Maximum Temperature} - \text{Minimum Temperature}}{2} - \text{Base Temperature} \qquad (1)$$

Basal corn crop coefficients (Kco) based on GDD and GS were taken from Hinkle et al. (1984). These crop coefficients were determined during the 1978, 1980, and 1981 growing seasons at the Sandhills Agricultural Laboratory [41°7′N, 100°50′W, 975 m amsl; soiltype: Valentine very fine sand to loamy fine sand (Typic Ustipsament)] and at Lincoln, Nebraska [40°49′N, 96°42′ W, 350 m amsl; soiltype: fine textured Sharpsburg silty clay loam (Typic Argiudolls)]. Weekly irrigations with overhead sprinklers replaced water losses as measured with a neutron probe. Evapotranspiration was measured with hydraulic lysimeters (Hanks and Shawcroft, 1965) modified to correct for changes in atmospheric pressure and temperature. The lysimeters had inside dimensions of 0.76 × 1.52 × 1.12 m. Lysimeter precision was ± 0.1 mm. Basal crop coefficients were determined from measurements taken when the soil surface was dry, or measurements were corrected for soil evaporation by the method of Hanks (1974). Eight corn hybrids used for crop coefficient determination ranged from 80 to 140 days to maturity. Regression coefficients were fit to the crop coefficient data from all sites and all years (table 2).

The Kco for the time-based crop coefficient method was taken from Kincaid and Heermann (1974); it was represented by the following equations:

$$\text{Kco} = 0.213 - 0.4276 \times X + 2.756 \times X^2 - 1.583 \times X^3 \qquad (2)$$

**Table 2. Corn crop coefficients (Kco) based on GDD and observed GS**

| X | Kco |
|---|---|
| **Growing Degree Day Method** | |
| $X \leq 0.12$ | $Kco = 0.15$ |
| $0.12 < X < 0.44$ | $Kco = -0.18 + 2.738 \times X$ |
| $0.44 \leq X \leq 0.81$ | $Kco = 1.02$ |
| $X > 0.81$ | $Kco = 3.208 - 2.698 \times X$ |
| where X = fraction of total GDD required for maturity | |
| **Growth Stage Method** | |
| $X \leq 0.69$ | $Kco = 0.15$ |
| $0.69 < X < 4.27$ | $Kco = -0.016 + 0.243 \times X$ |
| $4.27 \leq X \leq 8.17$ | $Kco = 1.02$ |
| $X > 8.17$ | $Kco = 2.74 - 0.211 \times X$ |
| where X = observed growth stage from Hanway (1974) | |

where X is fraction of days from planting to full cover, and

$$Kco = 0.915 + 0.01195 \times X - 4.688E\text{-}04 \times X^2 + 2.75E\text{-}06 \times X^3 \qquad (3)$$

where X is number of days after full cover, assuming full cover occurs at LAI of 3.0.

For the current study, additional evaporation from wet soil following rain or irrigation was computed as:

$$Eadd = Kr \times (0.9 - Kco) \times ETr \qquad (4)$$

where

Kr = 0.8 for the first day after rain or irrigation
= 0.5 for the second day after rain or irrigation
= 0.3 for the third day after rain or irrigation (Duke et al., 1985; Stegman, 1988)

Limits were placed on Eadd so that the summation of Eadd on days following rain or irrigation was always less than or equal to the amount of rain and/or irrigation. Eadd was set to 0 when Kco was greater than 0.9 (no evaporation from wet soil surface when full ground cover has been achieved).

The soil water stress coefficient which reduces Kco as soil water becomes limiting was considered negligible and ignored due to weekly irrigations which maintained available soil water above 50% (Boonyatharokol and Walker, 1979). Corn yields in the current study confirm that water stress was negligible, with average grain yields of 10 055 kg ha$^{-1}$ (1991) and 9624 kg ha$^{-1}$ (1992). [County average irrigated corn yields were 10 129 kg ha$^{-1}$ (1991) and 9032 kg ha$^{-1}$ (1992)].

Predicted corn ET (ETcorn) was calculated as:

$$ETcorn = Kco \times ETr + Eadd \qquad (5)$$

## RESULTS AND DISCUSSION

Throughout most of the corn growing season, 1992 was cooler than 1991, resulting in a slower rate of GDD accumulation (fig. 1). The three planting dates and three hybrids produced differences in date and duration of full cover conditions (LAI > 3.0) (fig. 2). Hybrid 3902 accumulated the least amount of leaf area, and maintained it for a shorter period of time than the other two hybrids. Hybrids 3732 and 3540 were more similar in their accumulation and retention of leaf area.

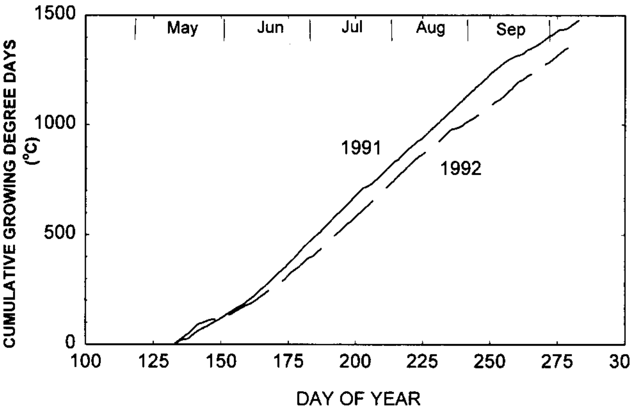

Figure 1–Cumulative 10-32 heat stress GDD vs. time for 1991 and 1992 at Akron, Colo.

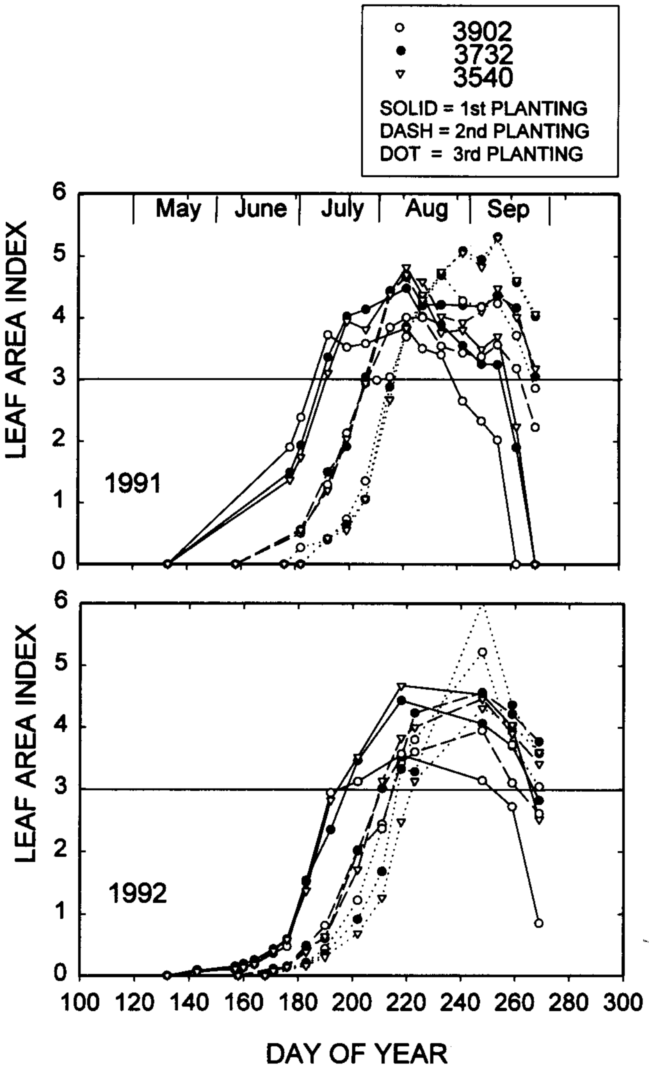

Figure 2–Leaf area index for the three corn hybrids and three planting dates for 1991 and 1992.

In our analysis of the predictive accuracy of the various Kco methods, we have divided the growing season into four periods corresponding to the segments of the GDD crop coefficient curve: segment 1, Kco = 0.15 plus first half of increasing linear Kco; segment 2, second half of increasing linear Kco; segment 3, Kco = 1.02; segment 4, declining linear Kco. The comparisons between predicted and measured ETcorn are shown graphically with ±10% error lines in figure 3 for each of the four segments and for the total growing season. Frequency distributions of the percent error in ETcorn predicted compared to measured are shown in figure 4.

Figure 3 shows that all three Kco methods did fairly well at estimating ETcorn for all three hybrids at all three planting dates in both years. Figure 4 shows that for segment 1 all three Kco methods had some instances overestimating ETcorn and some underestimating ETcorn. In general, the GDD Kco and the GS Kco underestimated ETcorn and the TB Kco overestimated ETcorn in segment 1. The comparisons of Kco values for selected

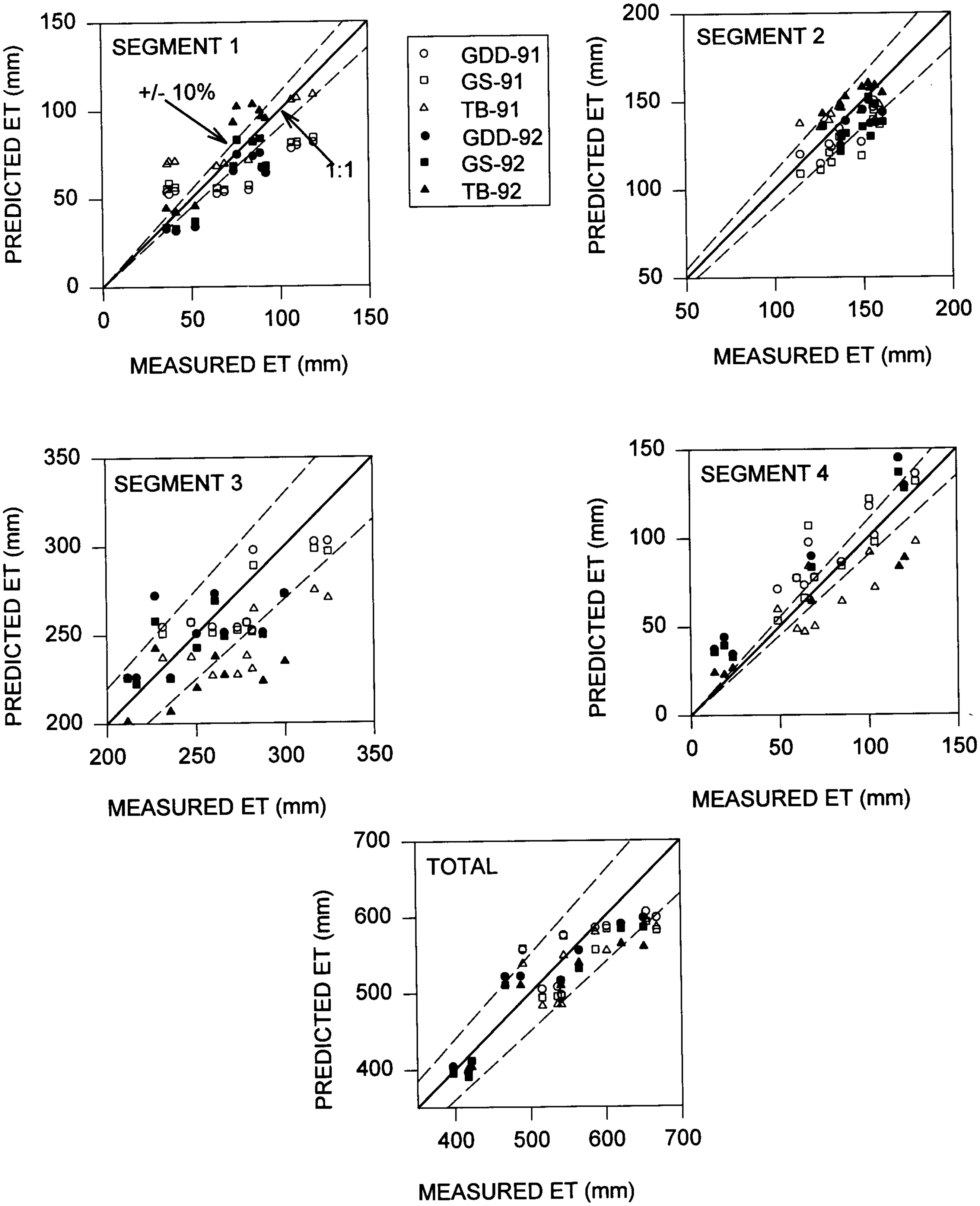

Figure 3–Measured vs. predicted corn ET for 1991 and 1992 at Akron, Colo., using crop coefficients based on GDD, GS, or time (TB). Solid line is 1 to 1 line; dashed lines are ±10% of measured ET value.

growth stages (table 3) show GS Kco and GDD Kco for growth stage 1 to be much lower than TB Kco. In segment 2, TB Kco mostly estimated within ±10% of measured ETcorn, while the GDD and GS methods underestimated ETcorn. During segment 3, the TB method underestimated ETcorn while the GDD and GS methods were estimating mostly within ±10% of measured ETcorn. In segment 4, the TB method continued to more often

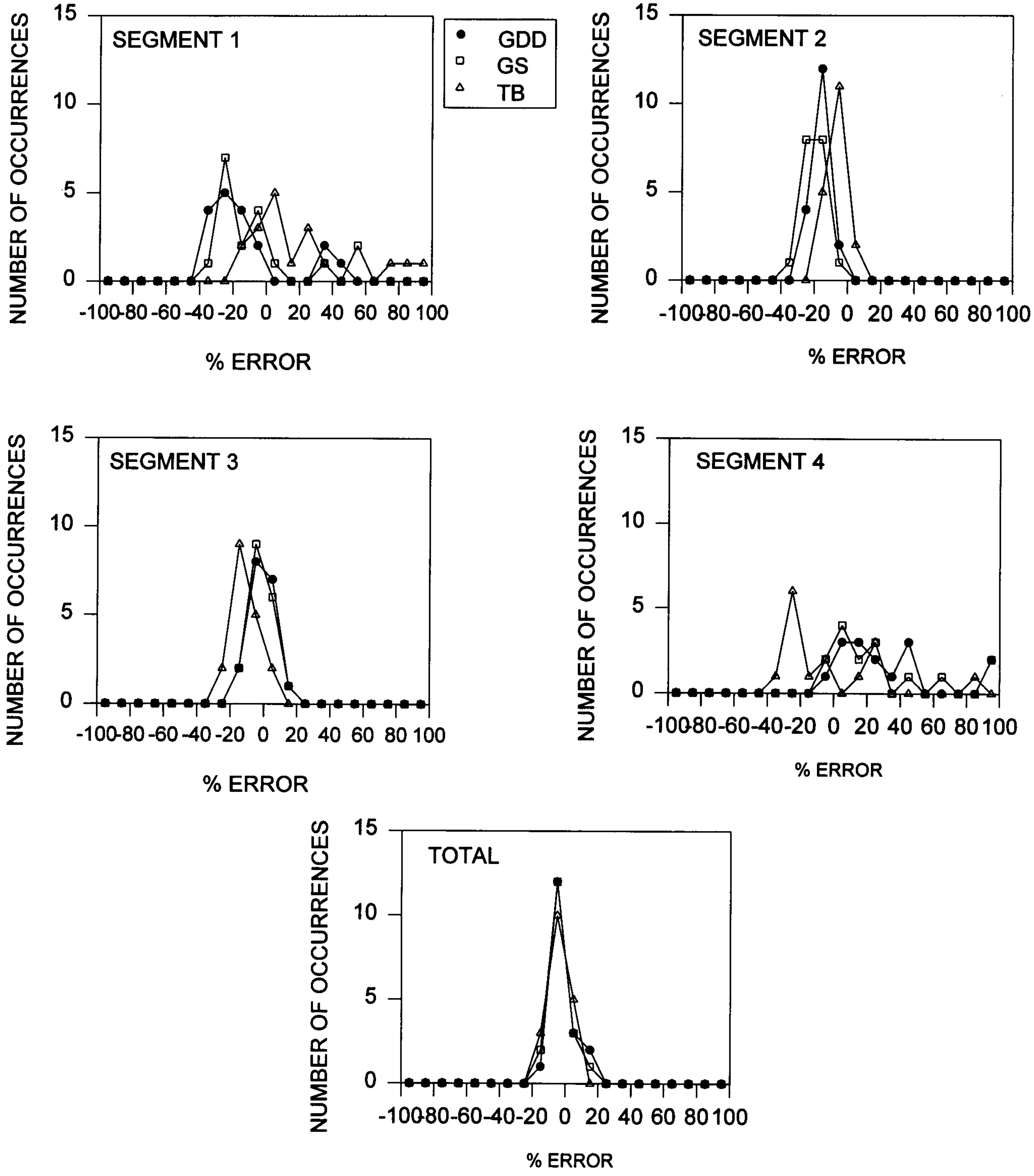

**Figure 4–Frequency distributions of percent error in corn ET prediction at Akron, Colo., during 1991 and 1992 using crop coefficients based on GDD, GS, or time (TB).**

underestimate ETcorn while the GDD and GS methods tended to overestimate ETcorn. All three methods were able to predict total growing season ETcorn within ±10% of measured for most of the planting date/hybrid combinations. The underestimation of ETcorn by the GDD and GS methods during the first half of the growing season was compensated for by overestimation during the last fourth of the growing season. On the other hand, overestimation of ETcorn by the TB method during the first fourth of the growing season was compensated for by underestimation during the last half of the growing season.

Even though 1992 was cooler than 1991 through much of the growing season, there were no systematic differences in the relative magnitudes of errors between the three Kco methods over the two years. Root mean square errors (RMSE) associated with ETcorn prediction (computed over

Table 3. Value of crop coefficient (Kco) based on GS, GDD, or TB for three corn hybrids (3902, 3732, 3540) planted at three dates at Akron, Colo., in 1991 and 1992

| GS Kco | | GDD Kco | | | | | | | | | TB Kco | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1991 | | 1st Planting | | | 2nd Planting | | | 3rd Planting | | | 1st Planting | | | 2nd Planting | | | 3rd Planting | | |
| Stage | | 3902 | 3732 | 3540 | 3902 | 3732 | 3540 | 3902 | 3732 | 3540 | 3902 | 3732 | 3540 | 3902 | 3732 | 3540 | 3902 | 3732 | 3540 |
| 1 | 0.23 | 0.15 | 0.15 | 0.15 | 0.18 | 0.16 | 0.15 | 0.15 | 0.15 | 0.15 | 0.53 | 0.54 | 0.54 | 0.38 | 0.38 | 0.34 | 0.41 | 0.41 | 0.37 |
| 3 | 0.71 | 0.81 | 0.85 | 0.86 | 0.81 | 0.81 | 0.78 | 0.79 | 0.85 | 0.79 | 0.93 | 0.94 | 0.95 | 0.81 | 0.84 | 0.86 | 0.96 | 0.95 | 0.96 |
| 5 | 1.02 | 1.02 | 1.02 | 1.02 | 1.02 | 1.02 | 1.02 | 1.02 | 1.02 | 1.02 | 0.99 | 1.00 | 1.00 | 0.96 | 0.99 | 1.00 | 1.00 | 0.98 | 0.99 |
| 7 | 1.02 | 1.02 | 1.02 | 1.02 | 1.02 | 1.02 | 1.02 | 1.02 | 1.02 | 1.02 | 0.94 | 0.93 | 0.89 | 0.97 | 0.93 | 0.90 | 0.90 | 0.84 | 0.68 |
| 9 | 0.81 | 0.94 | 0.89 | 0.95 | 0.86 | 0.92 | 0.82 | 0.95 | * | * | 0.68 | 0.63 | 0.60 | 0.75 | 0.70 | 0.45 | 0.48 | * | * |
| 1992 | | | | | | | | | | | | | | | | | | | |
| 1 | 0.23 | 0.20 | 0.15 | 0.15 | 0.15 | 0.15 | 0.15 | 0.15 | 0.18 | 0.21 | 0.53 | 0.46 | 0.48 | 0.44 | 0.47 | 0.50 | 0.40 | 0.44 | 0.43 |
| 3 | 0.71 | 0.87 | 0.78 | 0.81 | 0.74 | 0.76 | 0.77 | 0.71 | 0.82 | 0.83 | 0.95 | 0.91 | 0.96 | 0.85 | 0.92 | 0.95 | 0.88 | 0.95 | 0.92 |
| 5 | 1.02 | 1.02 | 1.02 | 1.02 | 1.02 | 1.02 | 1.02 | 1.02 | 1.02 | 1.02 | 1.00 | 0.99 | 0.99 | 0.94 | 1.00 | 0.99 | 0.98 | 1.00 | 0.99 |
| 7 | 1.02 | 1.02 | 1.02 | 1.02 | 1.02 | 1.02 | 1.02 | 1.02 | 1.02 | 1.02 | 0.92 | 0.92 | 0.83 | 0.99 | 0.92 | 0.83 | 0.93 | 0.86 | 0.86 |
| 9 | 0.84 | 1.02 | 0.95 | 0.87 | 1.02 | 1.01 | 0.98 | 1.01 | * | * | 0.67 | 0.58 | 0.38 | 0.75 | 0.57 | 0.40 | 0.58 | * | * |

* Crop did not make it to this GS due to frost (1991) or crop harvested for silage (1992).

planting times and hybrids) are given in table 4. Errors were almost always lower with the TB Kco in segments 1 and 2. During segment 3, errors were lower in both years using GDD and GS Kco than with TB Kco. For segment 4, the errors were lowest in 1991 with the GDD Kco and in 1992 with the GS Kco. The GDD and GS methods maintain a higher Kco and higher ETcorn for a longer period of time than the TB method. For the total growing season, errors were lowest with the GDD Kco in both years.

Root mean square errors computed by planting time and by hybrid are also given in table 4. These data show that no one Kco method predicted ET better for any given planting time or hybrid. The TB Kco produced more accurate ETcorn estimates for most of the planting dates and hybrids in segments 1 and 2, but the GDD and GS Kco had lower errors for most of the planting dates and hybrids in segments 3 and 4. The GDD Kco predicted total growing season ETcorn better than the TB Kco for the early and late planting dates and for hybrids 3732 and 3540.

## CONCLUSIONS

Crop coefficients developed in Nebraska based on GDD or GS can be used to predict corn ET in northeastern Colorado over a wide range of corn hybrid maturities, planting dates, and environmental conditions. These crop coefficients generally produce more accurate estimates of corn ET than time-based crop coefficients during the high water use period after full cover is achieved and as leaf area senesces. Time-based crop coefficients produce more accurate estimates of corn ET during the period of crop growth prior to full cover. Corn ET for the entire growing season is generally more accurately predicted with Kco based on growing degree days or observed growth stage than based on time. Crop coefficients based on observed growth stage or growing degree days simplify ET prediction and irrigation scheduling because adjustments for abnormal environmental conditions or planting dates are not necessary.

Table 4. Root mean square error of predicted ETcorn by year, planting time, and hybrid as affected by crop coefficient calculation method for growing season divided into four segments*

| | Segment 1 | | | Segment 2 | | | Segment 3 | | | Segment 4 | | | Total Growing Season | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | GDD | GS | TB | GDD | GS | TB | GDD | GS | TB | GDD | GS | TB | GDD | GS | TB |
| **Year†** | | | | | | | | | | | | | | | |
| 1991 | 2.48 | 2.39 | 2.05 | 1.22 | 1.78 | 1.20 | 2.01 | 2.08 | 3.96 | 1.68 | 1.77 | 2.13 | 4.43 | 5.29 | 5.27 |
| 1992 | 1.61 | 1.35 | 1.46 | 1.10 | 1.63 | 0.97 | 2.45 | 2.18 | 3.99 | 1.83 | 1.46 | 1.71 | 3.43 | 3.72 | 4.53 |
| Both | 2.03 | 1.88 | 1.73 | 1.13 | 1.66 | 1.06 | 2.17 | 2.07 | 3.86 | 1.70 | 1.57 | 1.88 | 3.84 | 4.44 | 4.77 |
| **Planting‡** | | | | | | | | | | | | | | | |
| Early | 2.98 | 2.73 | 1.04 | 1.58 | 2.33 | 0.75 | 2.21 | 2.39 | 4.80 | 1.90 | 1.20 | 2.76 | 4.72 | 6.19 | 6.75 |
| Mid | 1.41 | 1.51 | 2.93 | 1.19 | 1.61 | 1.17 | 2.81 | 2.31 | 3.67 | 2.31 | 2.50 | 1.66 | 4.54 | 4.28 | 4.01 |
| Late | 1.76 | 1.53 | 0.71 | 0.67 | 1.13 | 1.36 | 1.81 | 1.85 | 3.75 | 1.49 | 1.35 | 2.01 | 2.67 | 3.22 | 3.95 |
| **Hybrid§** | | | | | | | | | | | | | | | |
| 3902 | 2.64 | 2.42 | 1.75 | 0.68 | 1.20 | 1.02 | 2.40 | 1.73 | 2.41 | 2.25 | 2.17 | 1.31 | 4.10 | 4.55 | 4.02 |
| 3732 | 1.65 | 1.61 | 2.03 | 1.40 | 2.00 | 1.24 | 1.74 | 1.92 | 3.81 | 1.74 | 1.77 | 2.08 | 4.04 | 4.73 | 4.87 |
| 3540 | 2.07 | 1.89 | 1.73 | 1.38 | 1.97 | 1.10 | 2.70 | 2.80 | 5.50 | 1.97 | 1.53 | 2.94 | 4.11 | 4.89 | 6.12 |

* GDD = growing degree day method, GS = growth stage method, TB = time based method.
† Averaged across planting dates and hybrids.
‡ Averaged across years and hybrids.
§ Averaged across years and planting dates.

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